Interactions of Waves and River Plume and their Effects on Sediment Transport at River Mouth

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LONG-TERM GOALS

To develop a robust coastal/nearshore modeling system for river plume dynamics, sediment deposition/resuspension and inlet morphodynamics in a wave-dominated, high sediment yield and highly stratified environment.

OBJECTIVES

- To develop a detailed wave-resolving Reynolds-Averaged Navier-Stokes model for wave-current-sediment interactions in well-mixed and salt-stratified conditions.

- To study the interactions between tidal flow, waves and riverine outflow and their effects on sediment transport and morphodynamics using NearCOM and FVCOM.

- To develop parameterizations of critical intra-wave processes for wave-averaged and/or depth-integrated coastal modeling systems.

APPROACH

Morphology of an inlet or a river mouth is very dynamic due to complex hydrodynamics involving wave-current interactions (e.g., waves, tidal current, riverine outflow) and input/redistribution of sediments. When riverine outflow is weak, inlet hydrodynamics and morphodynamics are mainly controlled by interaction between tidal flow and bathymetry (de Swart & Zimmerman 2009). In addition, wave effects can further complicated (and sometimes dominates) this problem through wave-induced cross-shore and alongshore transports (Bhattacharya and Giosan 2003). Due to the nonlinear nature of the system, the effects of tidal currents and waves on the resulting hydrodynamics and sediment transport cannot be simply incorporated through linear additions. In fact, many theoretical, laboratory and field evidences suggest nonlinear interactions among waves, tidal currents, bathymetry, bottom boundary layer and sediment transport processes are the determining factors in coastal morphodynamics. These complex interactions give distinct channel-shoal patterns, river mouth bars and ephemeral deposits that are either very dynamic or in some sort of dynamic equilibrium.

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We envision a multi-scale numerical modeling of coastal hydrodynamics, sediment transport and morphodynamics for turbid riverine outflows into a coastal zone with strong tidal flow and wave energy that may be further complicated by bathymetry. The backbone of such modeling framework shall be built upon exiting coastal/nearshore modeling system. In the past decade, there has been significant progress in the numerical modeling of coastal/nearshore circulation, wave field and sediment transport (e.g., Reniers et al. 2004; Warner et al. 2008; Shi et al. 2003; Chen et al. 2003; Kim et al. 2009). However, there remains critical issues, especially related to coupling between wave and circulation, net transport rate associated with wave-current interaction and nonlinear wave statistics, flocculation, and convective sedimentation (and many others) that need to be investigated in details. Hence, our study can be discussed in terms of modeling at two different spatial and temporal scales, namely, the intra-wave scale and the coastal modeling scale.

Intra-wave scale: Understanding the intra-wave processes is a critical step to further predict large-scale coastal hydrodynamics and morphological evolution. To achieve our long term goal, we address three critical intra-wave processes:

(1) Wave-current interaction: the interactions between surface waves and tidal flow near inlet/river mouth with episodic large river outflow.

(2) Initial deposition: Processes affecting vertical sediment flux that may greatly alter the distribution of sediment deposition.

(3) Resuspension and transport: How interaction between waves and tidal flow can affect resuspension and re-distribution of sediment near inlet/river mouth.

A wave-resolving 2DV numerical model solving Reynolds-Averaged Navier-Stokes (RANS) equations with free-surface tracking scheme based on volume of fluid (VOF) method (e.g., Lin & Liu 1998) is extended by PI's team to study wave-mud interaction. This numerical model is able to resolve continuously and consistently the surface wave propagation, bottom boundary layer fluid-mud transport, and wave attenuation with a single set of governing equation and closures (Torres-Freyermuth & Hsu 2010). Recently, this code is further extended to calculate sediment-induced gravity flow and salinity transport (Snyder & Hsu 2011). This code is adopted here to study interactions between surface waves, currents and sediment transport processes. We have also started to extend our 2DV-RANS-VOF modeling effort to 3D turbulence resolving modeling of wave propagation and its interaction with shoreline and riverine outflow.

Coastal modeling scale: To model the hydrodynamics and morphodynamics of the entire estuary and inlet, numerical models that cover a spatial domain of tens of kilometers and temporal evolution of weeks to months are needed. Due to computational cost, these models are inevitably based on depth-integrated and/or wave-averaged formulations. While one of the main focuses of our modeling efforts is the intra-wave processes, it is also critical to carry out large-scale modeling so that critical issues related to morphodynamics can be investigated and more importantly, findings at the intra-wave scale can be directly implemented into the coastal modeling scale. Two open-source codes are implemented. For the first stage of the DRI (New River Inlet), we adopted a parallelized version of NearCOM-TVD (Shi et al. 2007; Shi et al. 2011), which couples a quasi-3D circulation model, SHORECIRC, with SWAN for waves. This code is computationally efficient comparing with other coastal models utilized in this DRI (see Impact/Application section) and hence we will be able to simulate hydrodynamics and morphological on a timescale of a month. In the second stage of the DRI, the unstructured grid, finite-

volume, three-dimensional (3D) primitive equation ocean model, FVCOM (Chen et al. 2003) will be adopted in order to simulate highly stratified river mouth processes.

WORK COMPLETED

We have extended the wave-resolving 2DV-VOF model to study wave-current interaction, the resulting turbulence structure in the water column and sediment resuspension. The numerical model is able to resolve both the bottom wave boundary layer and free-surface wave propagation concurrently over a water depth of 3~5 meter with a vertically stretched grid system. Model results suggest the numerical model is able to reproduce the enhanced (reduced) current intensity near the surface when waves propagate against (following) the current similar to earlier small-scale laboratory observation (e.g., Kemp and Simons 1982, 1983; van Rijn 1993). Concurrently, the model is able to predict the enhanced roughness of the current profile near the bed (i.e., apparent roughness; Grant and Madsen 1979). These main features are critical to further predict mixing and sediment transport in the water column. Recently, we adopt these wave-resolving results to evaluate the turbulence closure in a typical wave-averaged coastal models. Exsting theoretical studies on wave-current interaction mainly focus on the effect of waves on the circulation through modification of momentum balance (e.g., added with the gradient of radiontion stress). However, there are only few studies (if any) focus on the effect of waves on the two-equation closure of circulation model. Essentially, the existing turbulence closure in a typical circulation model does not include any effect of waves. When the wave effect is considered in a wave-averaged circulation model, the corrsponding turbulence kinetic energy is in fact a wave-averaged TKE. Consequently, it is not difficult to argue the existance of a intra-wave averaged production term (and flux term). Moreover, the intra-wave effects are also expected to depends on wave nonlinearity. The 2DV-VOF model results can be used to expand the two-equation turbulence closure when wave effects beome critical.

Because the hydrodynamics around the New River Inlet is more or less well-mixed, we utilized a new version of the Nearshore Comminuty Model System (NearCoM) as the primary modeling tool in the large-scale. NearCoM was the main product of the NOPP-Nearshore Community Model initiative in 2002 (Shi et al. 2005). Since then, Co-PI Fengyan Shi have made several enhancements to the versoin of NearCoM that we utilized in this project. Shi et al. (2011) integrated the wave model SWAN and a modified version of SHORECIRC in the NearCoM framework. Specifically, the model is incorporated with tide, wind and atmosphereic pressure forcing as well as Coriolis force, which expands the applicability of NearCoM to inner shelf and river/inlet. In FY11, Co-PI Shi further enhanced SHORECIRC with a hybrid finite-volume and finite-difference (MUSCLE-TVD) scheme. Parallized version (MPI) of coupled SHORECIRC and SWAN is recently completed in order to efficiently compute large-scale problem. The resulting model is now named NearCoM-TVD.

RESULTS

NearCoM-TVD simulation of wave-current hydrodynamics of New River Inlet is presented in Figures 1 and 2. The figures show tide and wave-induced nearshore currents (arrows) predicted by SHORECIRC and significant wave height (color) predicted by SWAN in the tightly coupled system. The model is forced with a tidal harmonic constant (M2 with an amplitude of 1 m) and offshore wave condition along the open boundaries. The input wave spectrum is assumed constant in time with a significant wave height of 2 m and an obliquely incident angle of about 30 degrees relative to the coastline. Alongshore currents are found persistently toward northeast at both ebb tide (Figure 1) and flood tide (Figure 2). Notice that further mesh refinement can be carried out in order to resolve more

detailed processes. NearCoM-TVD provide us with a good hydrodynamic framework that will be coupled with various sediment transport formulation in order to investigate morphological evolution over a timespan of the proposed field expriment in 2012.

Hsu et al. (2006) demonstrated the importance of wave skewness and the parameterization of current friction factor (under the influence of waves) in determining onshore transport and sandbar migration. They provided a revised Bailard (1981) formula which better parameterizes the effect of wave on current induced transport. In this DRI, we like to further investigate this issue in the context 3D morphologcial evolution and more complex tidal inlet setting using NearCoM-TVD. Several sediment transport modules will be incorporated to study different mechanisms in driving sediment transport (e.g., Soulsby 1997; Bailard 1981; Drake and Calantoni 2001; Hsu et al. 2006). One of the key physical quantities in determining wave-induced sediment transport is wave skewness. Because SWAN does not provide nonlinear wave statistics, accurate parameterizations of wave skewnss is the most critical task before net sediment transport rate can be estimated. Several empirical parameterizations will be adopted and evaluated in this study (e.g., Elfrink et al. 2006). More accurate information on nonlinear wave statistics will be investigated through collaobration with Boussinesq wave modelers in this DRI.

IMPACT/APPLICATIONS

Our small-scale modeling effort will improve our existing understanding on the effects of wave-current interaction on the full-depth vertical flow structure, mixing and sediment transport and provide improved parameterizations for coastal models. Our coastal modeling effort using NearCoM-TVD for the proposed field site at New River Inlet provides a modeling alternative using more efficient quasi-3D formulation which is complementary to other participants in this DRI utilizing Delft3D, time-domain and frequency domain Boussinesq wave models. PI Hsu has an ongoing NSF project to study the dynamics of sediment-laden river plume and initial deposition off small mountainous rivers. FVCOM is also used in this NSF project for large-scale coastal modeling of Gaoping river mouth – submarine canyon system. FVCOM modeling can be used in the second stage of the DRI if a stratified river mouth is investigated.

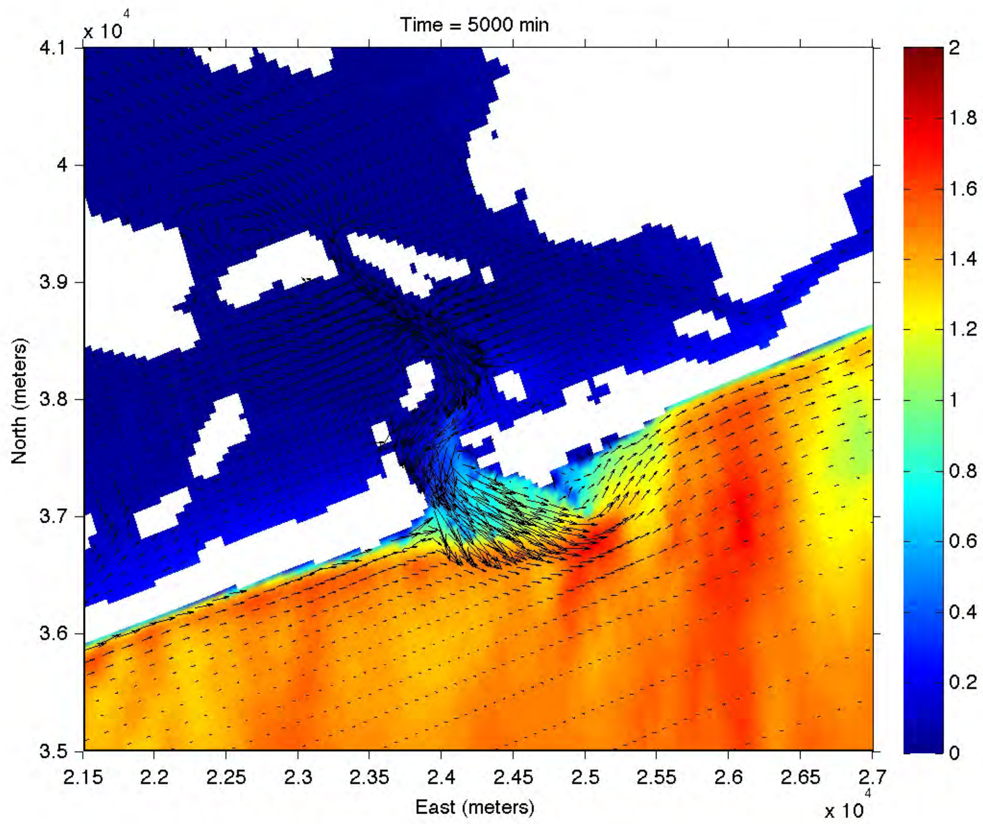

Figure 1: Nearshore currents (arrows) and wave height (color) during maximum ebb tide predicted by NearCoM-TVD.

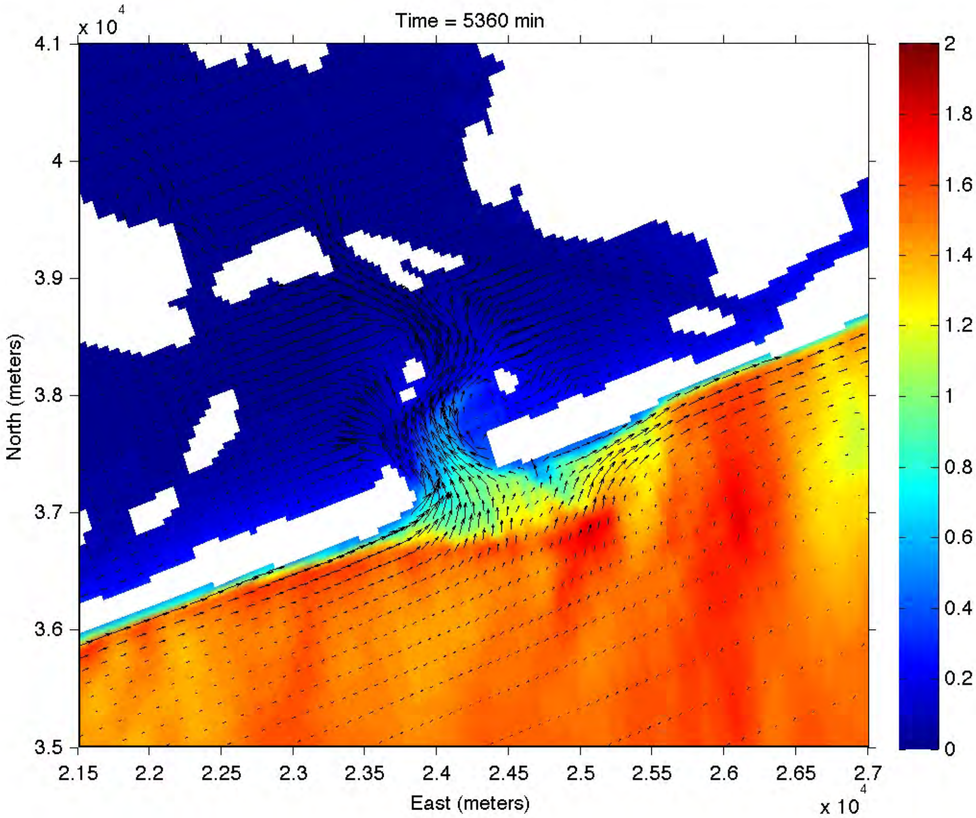

Figure 2. Nearshore currents (arrows) and wave height (color) during maximum flood tide predicted by NearCoM-TVD.

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